Transverse Λ polarization at high energy colliders

Daniël Boer
VU University Amsterdam

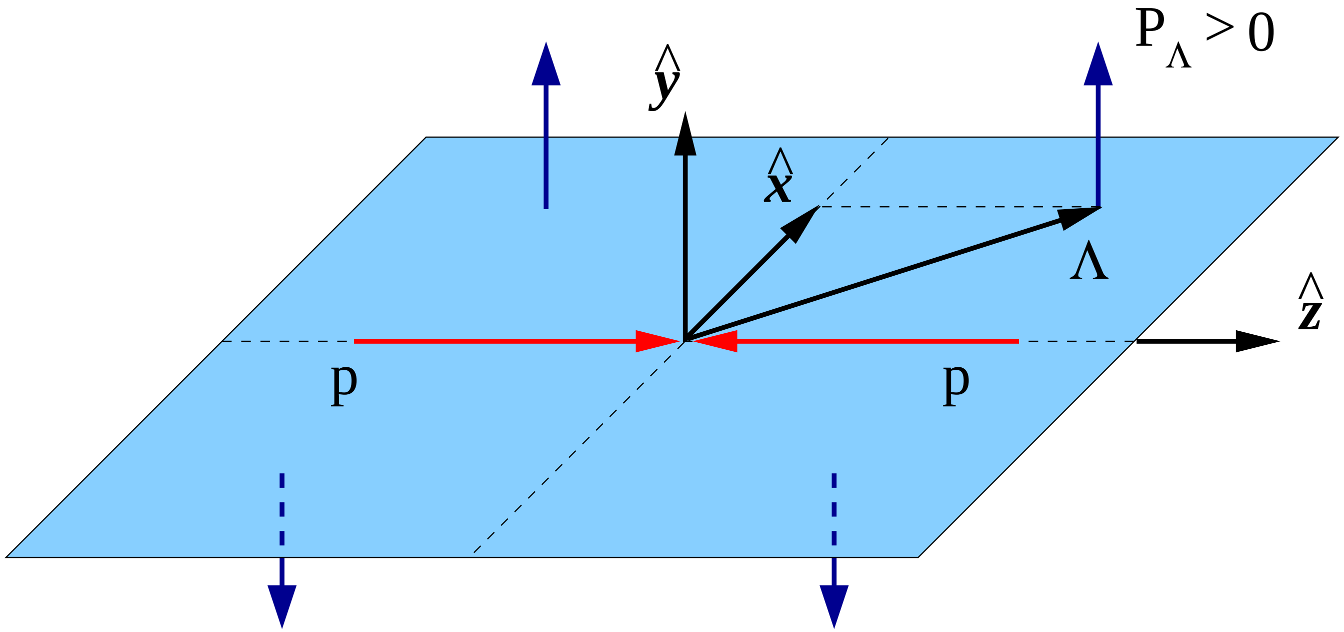
Outline

- Brief review of transverse Λ polarization in $p + p \to \Lambda + X$: data & features
- Theoretical considerations: models and pQCD expectations
- Possible underlying mechanism in the intermediate to high $\boldsymbol{p}_T$ region: transverse momentum and spin dependence in the fragmentation process
- Analysis of $p + p(Be) \to \Lambda^\uparrow(\bar{\Lambda}^\uparrow) + X$ data and application to:
  - semi-inclusive DIS: $\ell + p \to \ell' + \Lambda^\uparrow + X$
  - $p + p \to \Lambda^\uparrow + \text{jet} + X$ at midrapidity
  - $p + Pb \to \Lambda^\uparrow + X$ in the forward region to probe saturation physics

Transverse Λ polarization in unpolarized scattering

Large asymmetries have been observed in $p + p \to \Lambda^{\uparrow} + X$

G. Bunce *et al.*, PRL 36 (1976) 1113

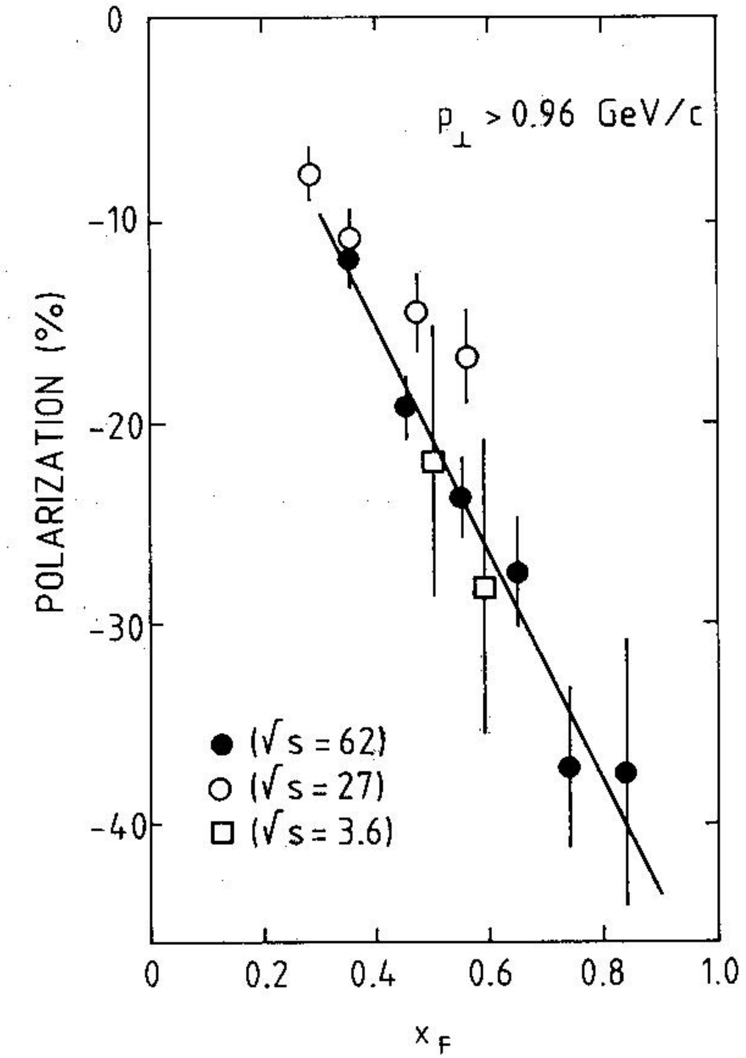


Blue arrows indicate the direction of positive transverse (w.r.t. production plane) polarization P_Λ, in the four quadrants

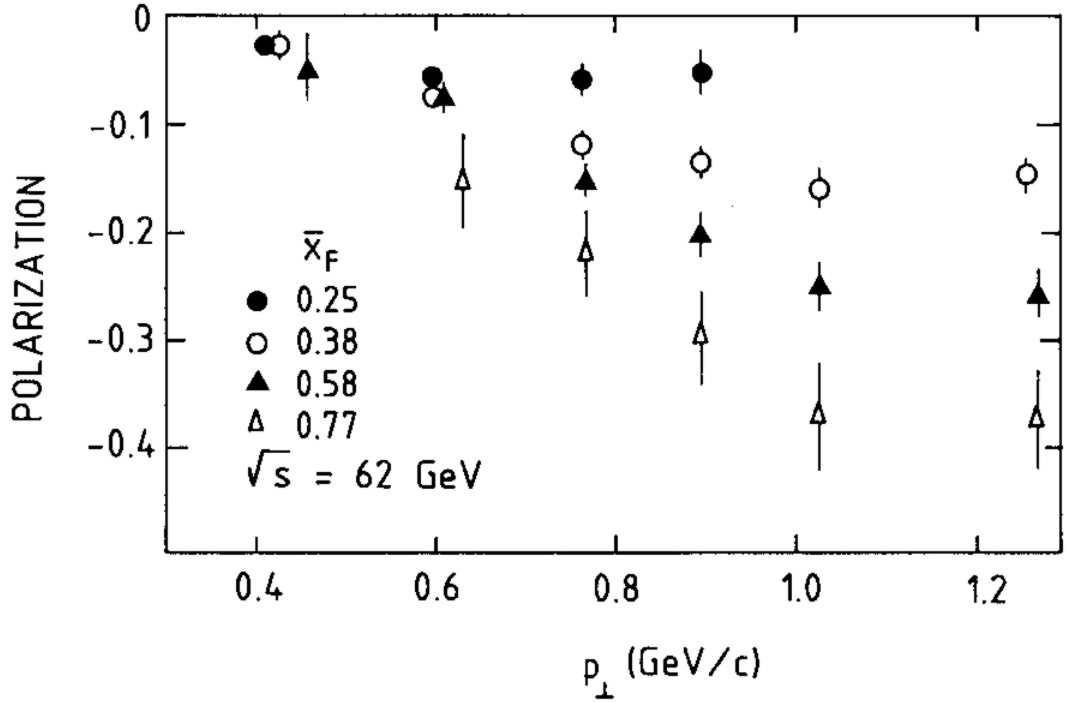
For symmetry reasons $P_\Lambda = 0$ at midrapidity

Data & Features

Generic $p\,p$ data - x_F and p_T dependence

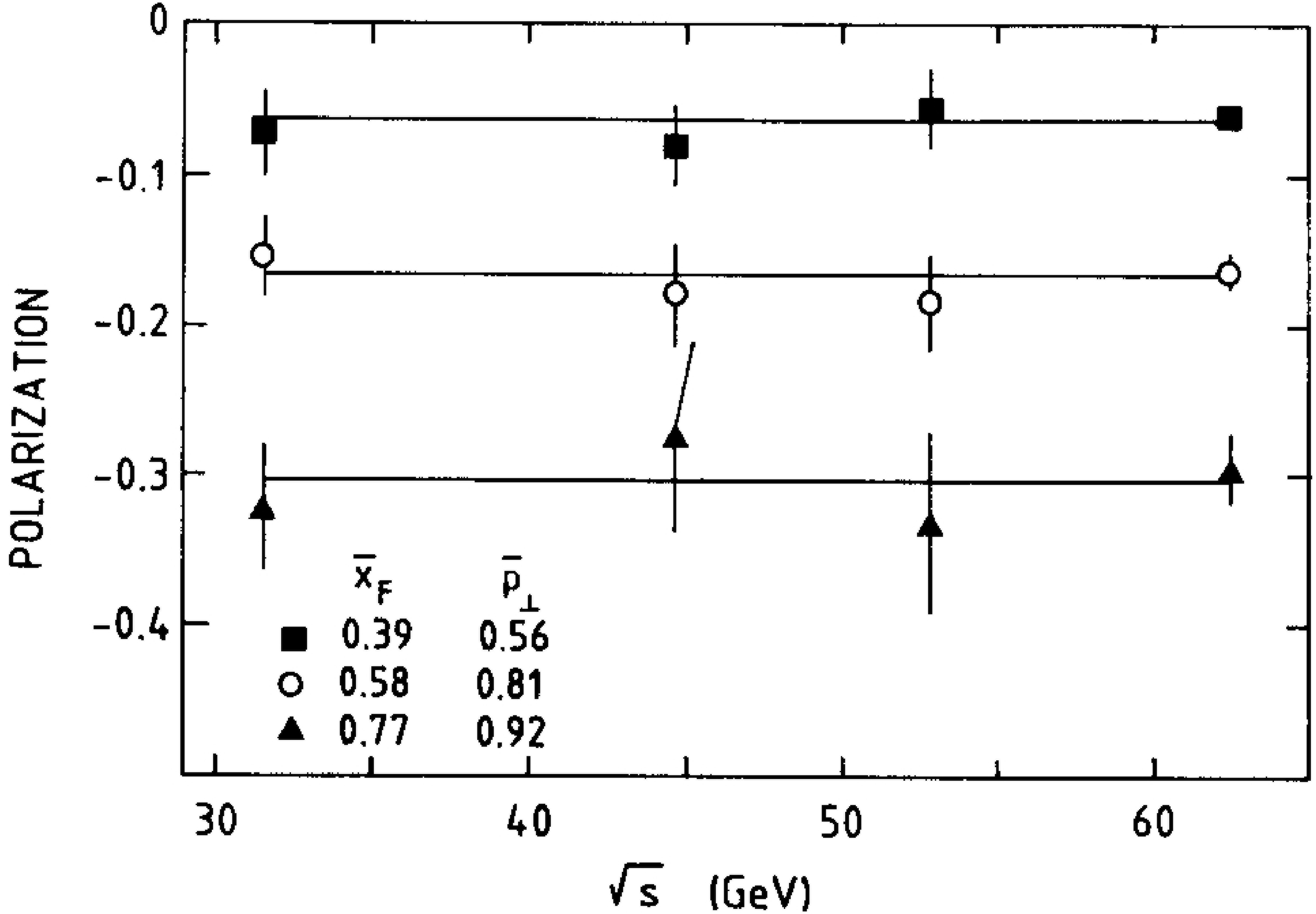


P_Λ turns out to be negative



For p_T above 1 GeV$/c$ P_Λ becomes flat

Generic pp data - $\sqrt{s}$ dependence



Transverse Λ polarization in unpolarized scattering

Features of the asymmetry:

- $P_\Lambda < 0$
- Magnitude grows with $x_F = 2p_L/\sqrt{s}$ and p_T ($\lesssim 1$ GeV$/c$)
- For $p_T \gtrsim 1$ GeV$/c$ it becomes flat (measured up to 4 GeV/c)
- For very large p_T it should fall off, but is not seen
- To a large extent $\sqrt{s}$ independent

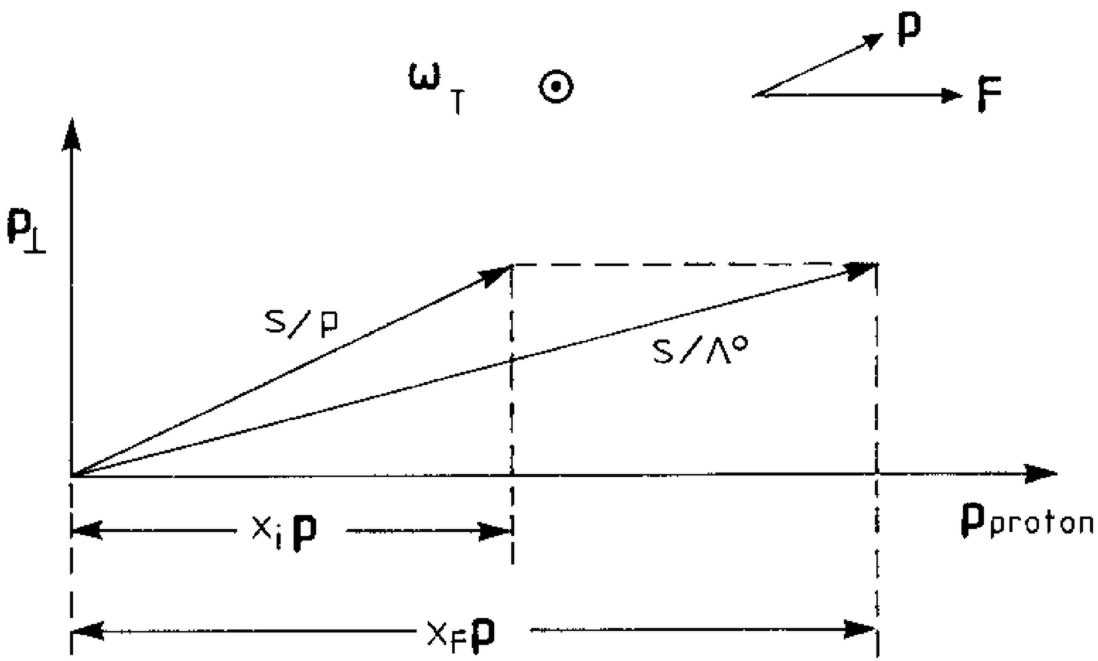
Comprehensive review of data by A.D. Panagiotou (Int.J.Mod.Phys.A 5 (1990) 1197)

Theory

Theoretical considerations

Perturbative QCD conserves helicity, which leads to $P_\Lambda \sim \alpha_s m_q/\sqrt{\hat{s}}$ (= small)
Kane, Pumplin & Repko, PRL 41 (1978) 1689

Many QCD-inspired models have been proposed, mostly based on
recombination of a ud diquark from the proton and an s quark from the sea
Spin-orbit coupling creates the polarization



The DeGrand-Miettinen model
PRD 23 (1981) 1227 & 24 (1981) 2419

Theoretical considerations

A comprehensive review of models by J. Felix (Mod.Phys.Lett.A 14 (1999) 827-842)
"In general, all models fail in fitting well the available experimental data on Λ polarization"

Most models give qualitative descriptions of the data for $p_T \lesssim 1 - 2$ GeV$/c$

However, for larger p_T, the recombination picture should become less adequate

Some models do yield p_T independence for larger p_T, but magnitude not calculable
E.g. Troshin & Tyurin, hep-ph/0501004

Predictability is often restricted to consistency of signs of Λ polarization from different beams $(\pi^{\pm}, K^{\pm}, \bar{p})$ and for different hyperons, using $SU(3)$

How to explain that the large asymmetry persists at least to $p_T \approx 4$ GeV$/c$?

For large p_T perturbative QCD and collinear factorization should apply

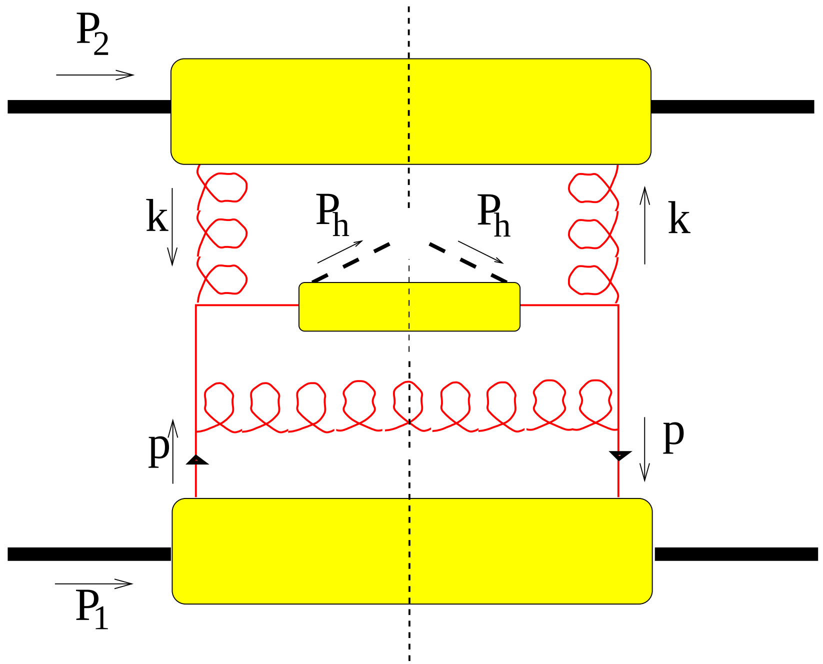
Collinear factorization

Consider for example the $qg \to qg$ subprocess

$$\sigma \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg\to qg} \otimes D_{\Lambda/q}(z)$$

$$q(x_1) = \text{quark density}$$
$$g(x_2) = \text{gluon density}$$
$$D_{\Lambda/q}(z) = \Lambda \text{ fragmentation function}$$

$$P_\Lambda \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg\to qg} \otimes ?$$

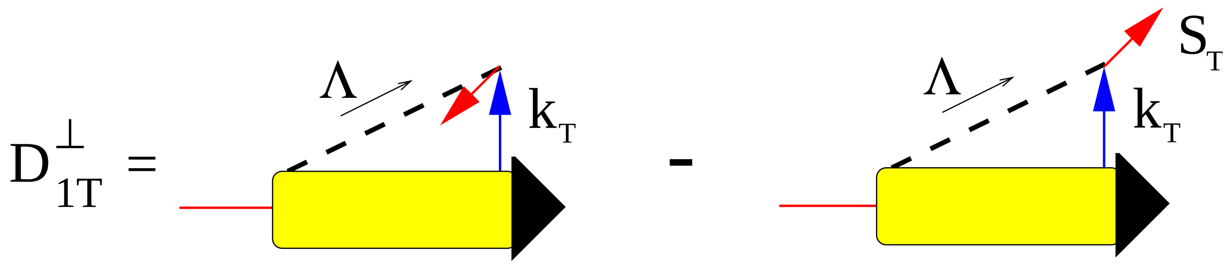


No leading twist collinear fragmentation function exists for $q \to \Lambda^\uparrow X$
(due to symmetry reasons)

Would be necessarily higher twist, which leads to a fall-off as $1/p_T$

Noncollinear factorization

Dropping the requirement of *collinear* factorization, does allow for a solution



Mulders & Tangerman, NPB 461 (1996) 197

- Transverse momentum dependent: $D_{1T}^{\perp}(z, \boldsymbol{k}_T)$
- A nonperturbative $\boldsymbol{k}_T \times \boldsymbol{S}_T$ dependence in the fragmentation process
- Allowed by the symmetries (parity and time reversal)

Λ polarization arises in the fragmentation of an *unpolarized* quark

Hence, the suggested name "polarizing fragmentation function"

Extraction of $D_{1T}^{\perp}$

Extraction of $D_{1T}^{\perp}$

Fit of $D_{1T}^{\perp}$ from available $p\,p(Be) \to \Lambda^{\uparrow}(\bar{\Lambda}^{\uparrow})\,X$ data

M. Anselmino, D.B., U. D'Alesio, F. Murgia, PRD 63 (2001) 054029

Assumptions:

- Λ polarization is generated in the fragmentation process
- Neglect $\boldsymbol{k}_T$ effects in the unpolarized initial nucleons
- Consider effective Λ FF's, including secondary Λ's ($\Sigma \to \Lambda\gamma$, etc)
- Polarizing FFs are strongly peaked around an average $k_{\perp}(z)$
- z dependence parameterized as $N z^{a}(1-z)^{b} D_1(z)$
- Consider only leading or valence quarks in the polarized fragmentation process
- Chiral-odd contributions are neglected

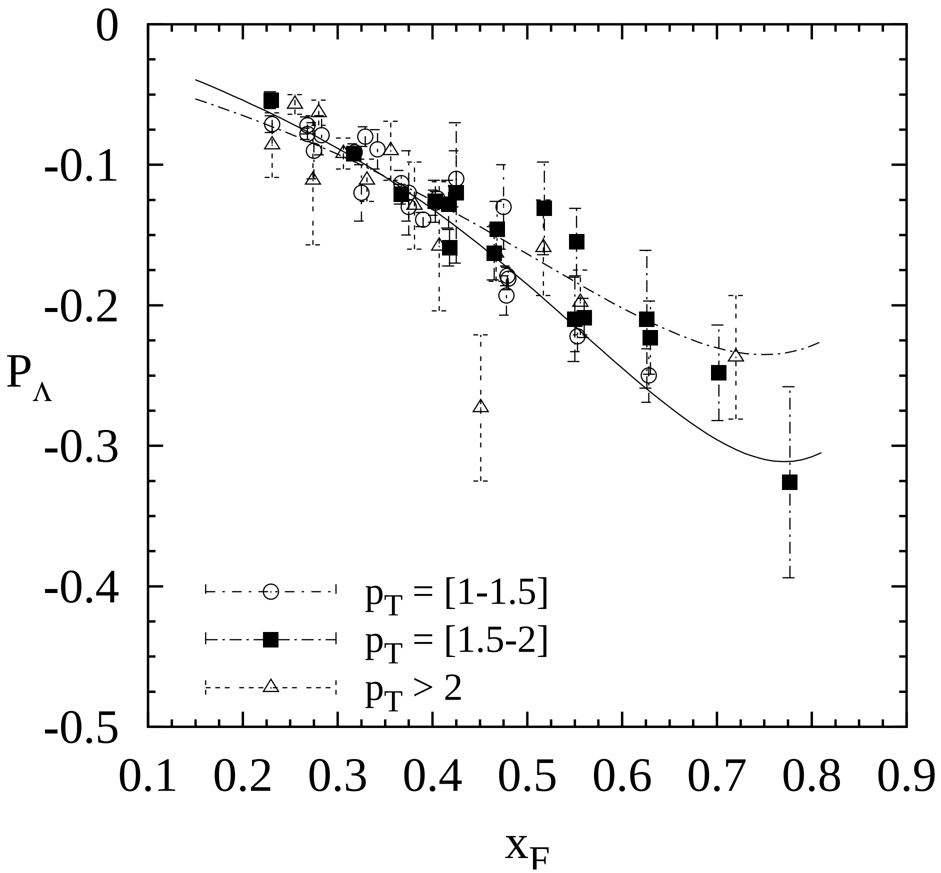
  Kanazawa & Koike, PRD 64, 034019 (2001) & hep-ph/0012005

  Zhou, Yuan, Liang, PRD 78 (2008) 114008

Furthermore:

- Impose appropriate positivity bounds
- Select data with $p_T > 1$ GeV$/c$ to exclude the soft regime

P_Λ: x_F dependence



P_Λ in p–Be reactions

Data are taken at $\sqrt{s} \simeq 28$ GeV and 40 GeV:

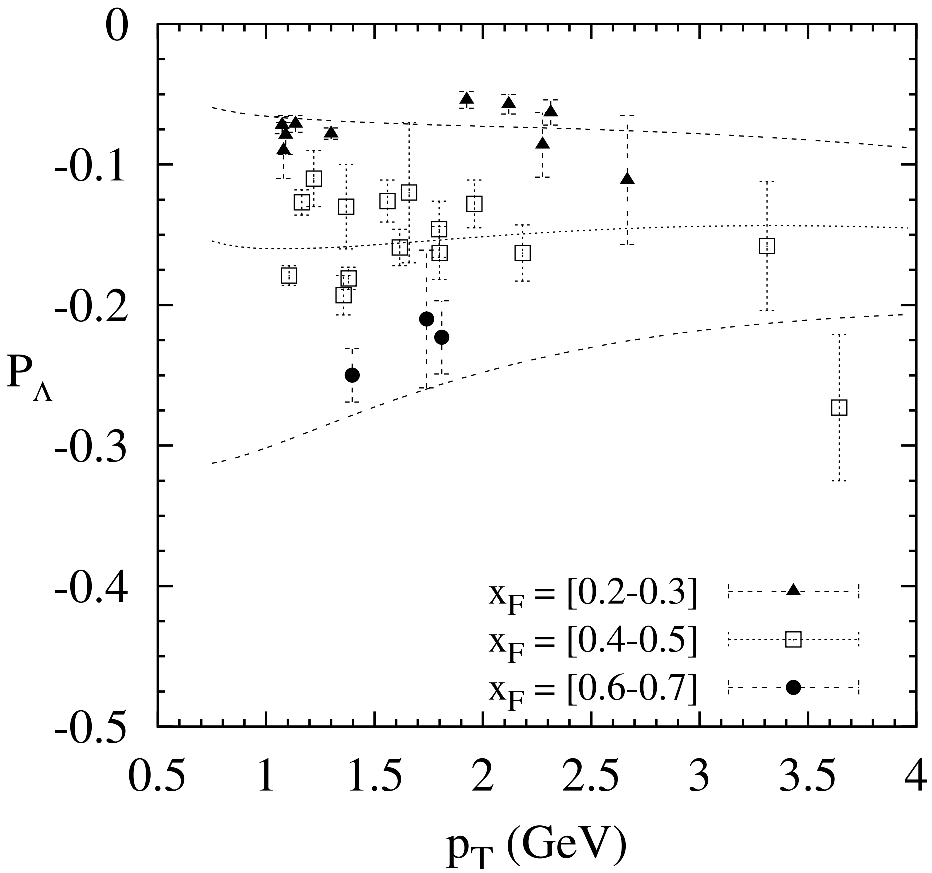
K. Heller et al., PRL 51 (1983) 2025

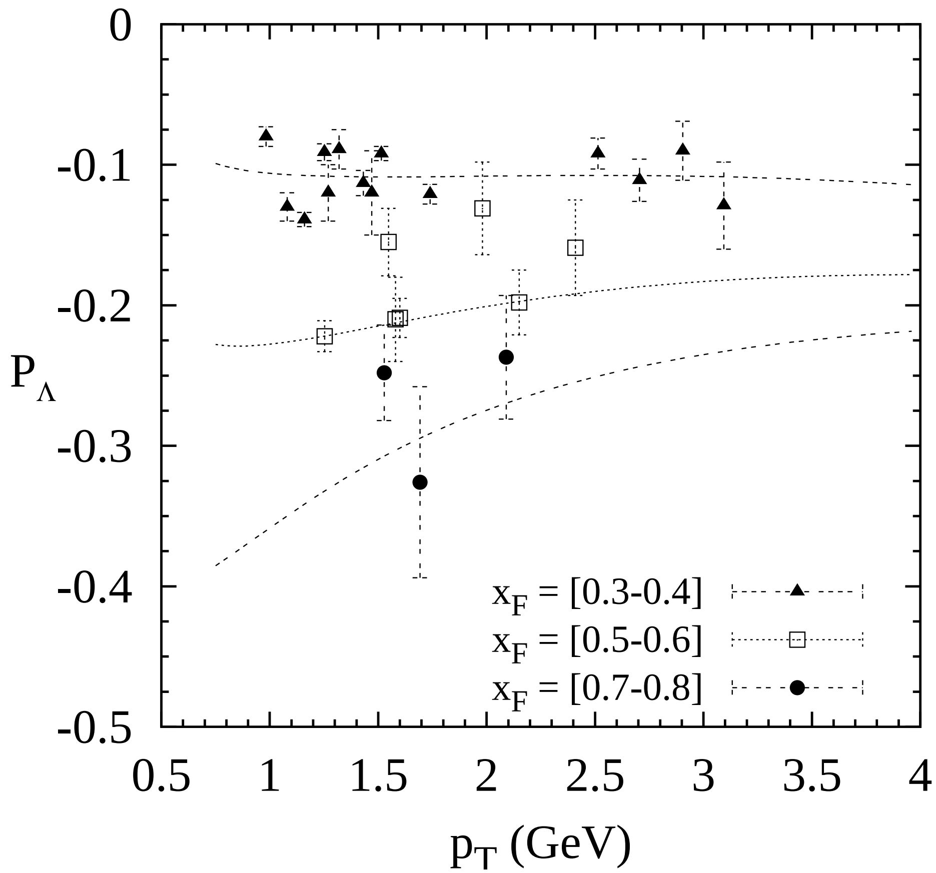
B. Lundberg et al., PRD 40 (1989) 3557

E.J. Ramberg et al., PLB 338 (1994) 403

The fitted curves are at $\sqrt{s} = 26$ GeV and at
$p_T = 1.5$ GeV/c (solid) and $p_T = 3$ GeV/c (dot-dashed)

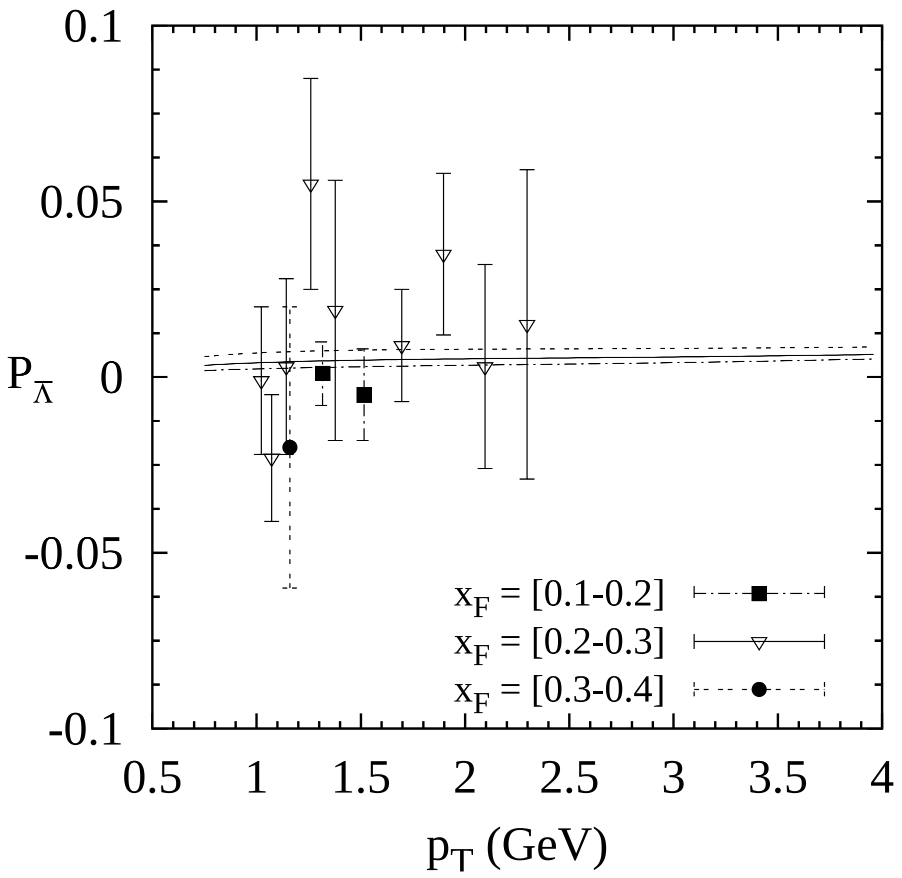
P_Λ: p_T dependence





The fitted curves are at $\sqrt{s} = 26$ GeV and at the mean x_F of a bin

$P_{\bar{\Lambda}}$: p_T dependence



$P_{\bar{\Lambda}}$ in p–Be reactions

Data are taken at $\sqrt{s} \simeq 28$ GeV:

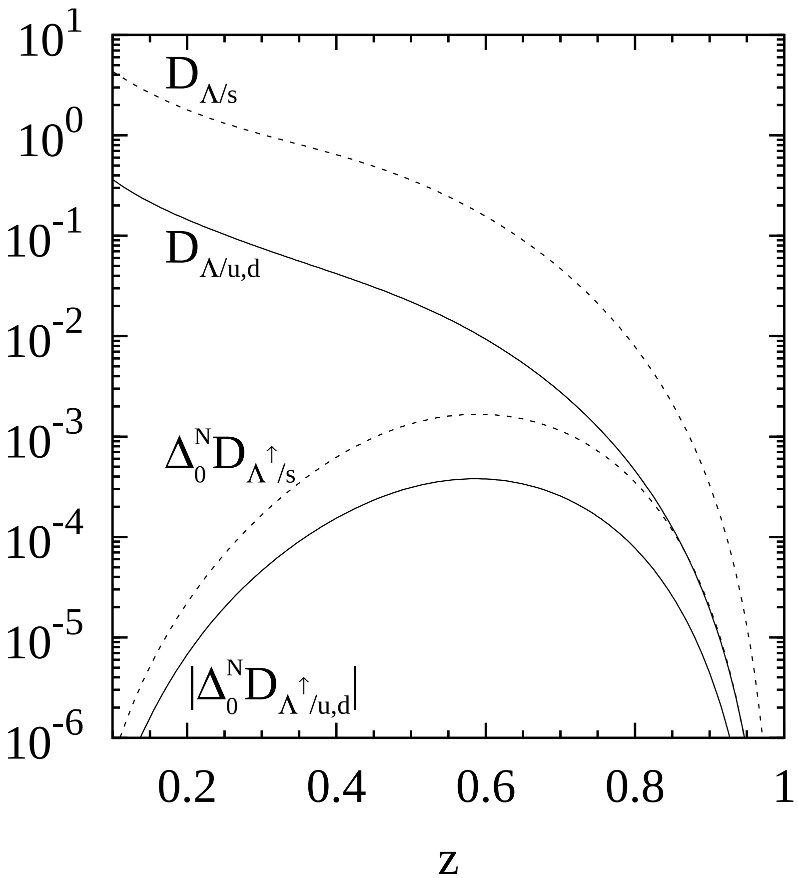
K. Heller et al., PRL 41 (1978) 607

E.J. Ramberg et al., PLB 338 (1994) 403

The fitted curves are at $\sqrt{s} = 26$ GeV and at the mean x_F of a bin

$P_{\bar{\Lambda}} \approx 0$ is the result of cancellations

z dependence



$D_{\Lambda/q}$ = unpolarized fragmentation function

$\Delta_0^N D_{\Lambda^\uparrow/q} \sim \langle k_\perp \rangle \, D_{1T}^\perp(z, \langle k_\perp \rangle)$ [# densities]

$D_{1T}^\perp$ has opposite signs for u, d versus s quarks; the latter is larger

This is the origin of the cancellations in $P_{\bar{\Lambda}}$

Note: ratios $\Delta_0^N D_{\Lambda^\uparrow/q}/D_{\Lambda/q}$ only sizeable for $z \gtrsim 0.5$

Theoretical issues

$D_{1T}^{\perp}$ is thought to be universal, despite its potential color flow dependence

Metz, PLB 549 (2002) 139; Gamberg, Mukherjee, Mulders, PRD 77 (2008) 114026

Meissner, Metz, 0812.3783/hep-ph; Yuan, Zhou, 0903.4680/hep-ph

Extraction done under the restriction of $p_T > 1$ GeV$/c$ to exclude the soft regime

Whether this is sufficient to ensure the validity of the description is a matter of concern

Nevertheless, reasonable functions are obtained

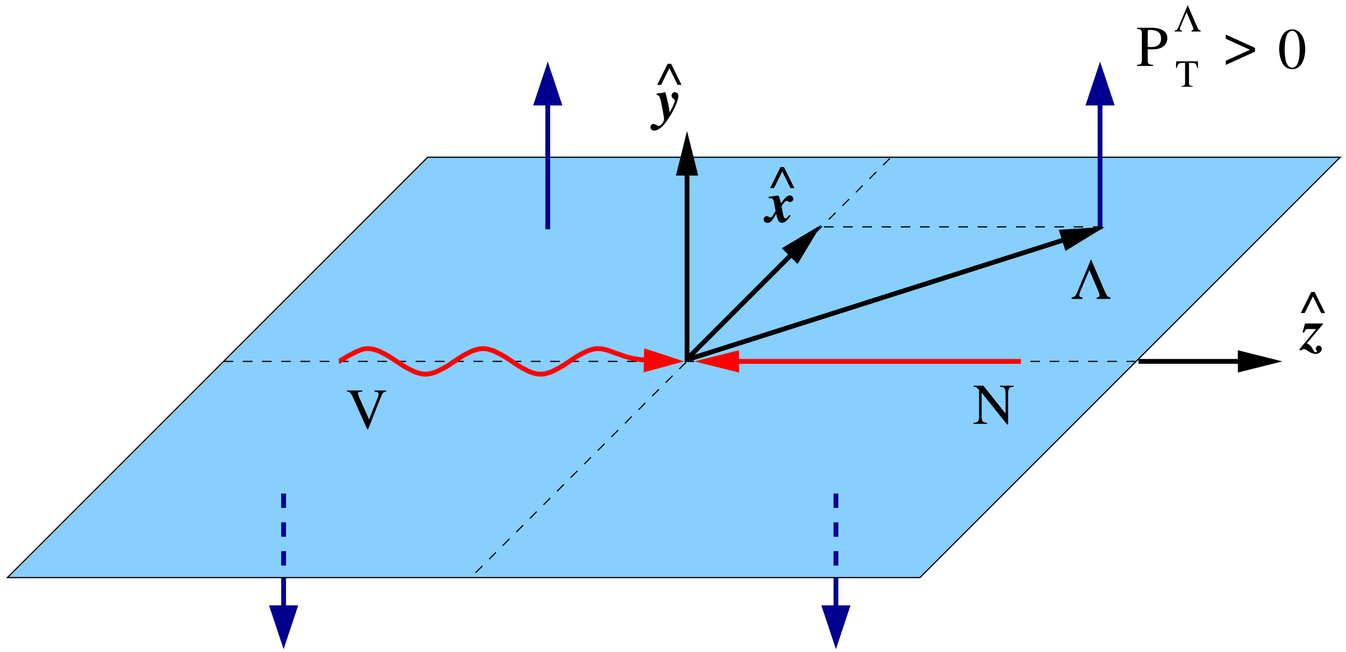
Note that same issue arises for single spin asymmetries A_N

Asymmetries at $\sqrt{s} = 20$ GeV and $\sqrt{s} = 200$ GeV are similar

At $\sqrt{s} = 200$ GeV the cross section is well-described by NLO pQCD

Semi-Inclusive DIS

SIDIS: $\ell\, p \to \ell'\, \Lambda^{\uparrow}\, X$



In order to have a factorized description of the cross section, Q^2 must be large

One can then only address the current fragmentation region $x_F > 0$

Since in SIDIS only Q^2 is required to be large, p_T^2 can be small

Model for the polarizing FFs needs more details on $k_\perp$ dependence than in $p\,p$ case

SIDIS data

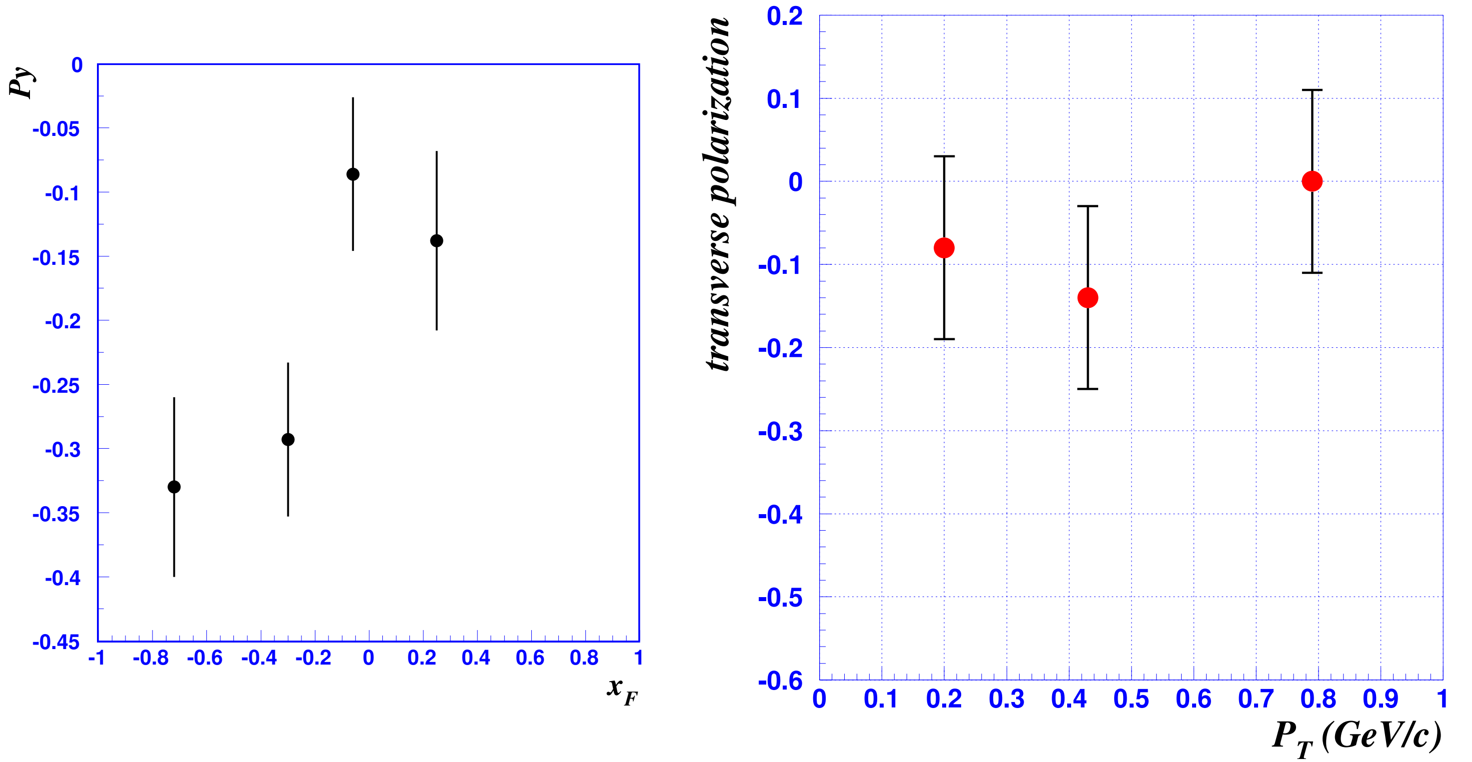
No neutral current SIDIS data avialable yet, except for $e\,p \to \Lambda^{\uparrow}\,X$ (quasi-real $Q^2 \simeq 0$)

Airapetian *et al.*, HERMES Collab., PRD76 (2007) 092008

Ferrero, for COMPASS Collab, SPIN2006 proceedings, p. 436

There is charged current SIDIS data by NOMAD on $\nu_\mu\,p \to \mu\,\Lambda^{\uparrow}\,X$

Astier *et al.*, NOMAD Collab., NPB 588 (2000) 3



Right plot:
$\langle x_F \rangle = 0.21$

Λ polarization in SIDIS

For current fragmentation ($x_F > 0$) transverse polarization: $P_y = -0.10 \pm 0.06$
Astier *et al.*, NOMAD Collab., NPB 588 (2000) 3

No significant transverse polarization has been found for the $\bar{\Lambda}$ sample
Astier *et al.*, NOMAD Collab., NPB 605 (2001) 3

In charged current exchange processes chiral-odd functions do not contribute
So could be used as a way to check their importance

NC and CC SIDIS studied using the fitted functions $D_{1T}^{\perp}$
Anselmino, D.B., D'Alesio & Murgia, hep-ph/0109186v1

Also studied using various model scenarios for $D_{1T}^{\perp}$
Anselmino, D.B., D'Alesio & Murgia, PRD 65 (2002) 114014

Λ polarization in SIDIS from $D_{1T}^{\perp}$

Following results for transverse Λ polarization in SIDIS used:

- Unpolarized Λ fragmentation functions:

  1) Indumathi *et al.* [IMR] (PRD 58 (1998) 094014)

  2) Boros *et al.* [BLT] (PRD 61 (2000) 014007) — SU(3) symmetric

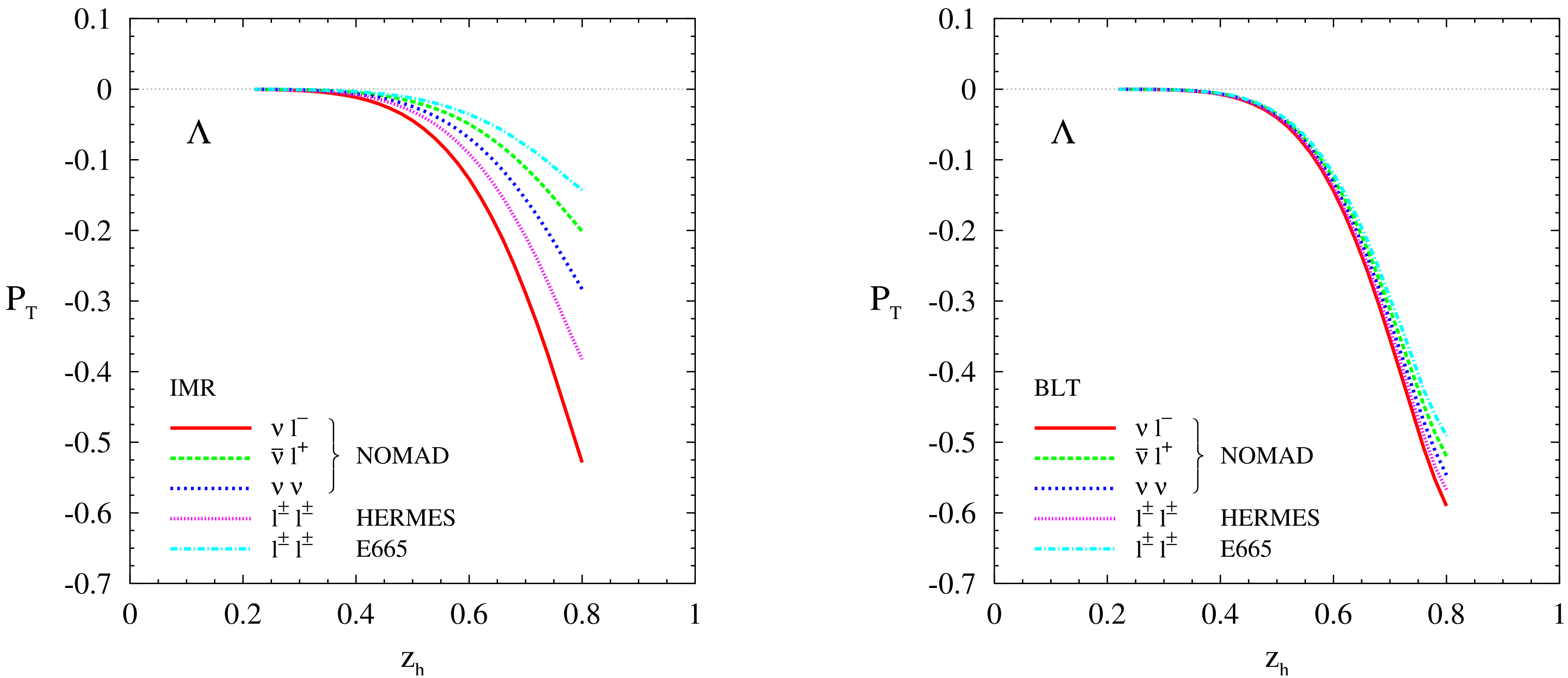
  De Florian *et al.* [DSV] (PRD 57 (1998) 5811) yields similar results as BLT if $P_T^{\Lambda+\bar{\Lambda}} \simeq P_T^{\Lambda}$

- Fitted polarizing FFs modified to have Gaussian transverse momentum dependence

Results will be shown for typical HERMES, NOMAD and E665 kinematics

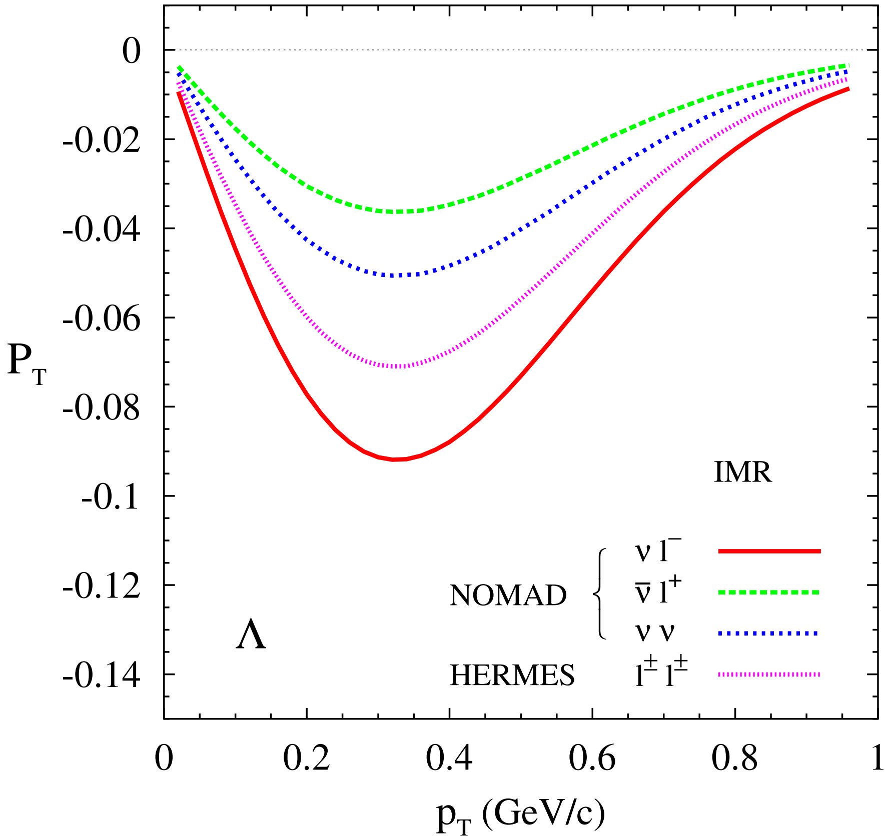
Q^2 is fixed to be 2 GeV^2 (approximately corresponding to the average p_T^2 in $p\,p \to \Lambda\,X$)

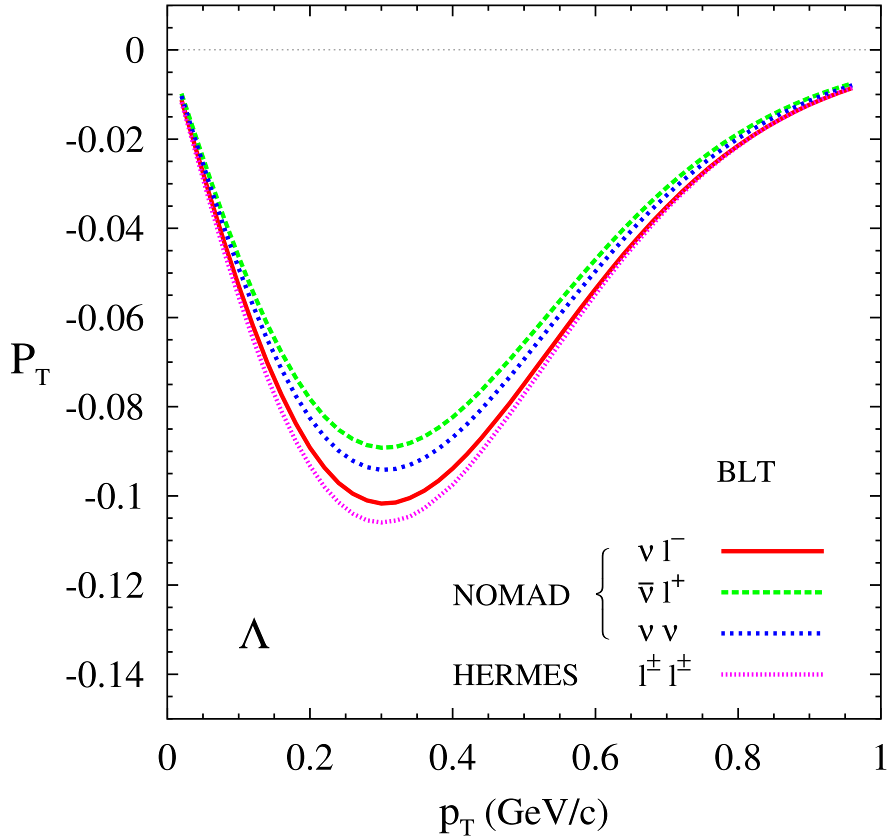
P_T: z_h dependence; averaged over p_T



- Asymmetry negligible below $z_h < 0.4$
- In SU(3) symmetric case the strange quark contribution is always suppressed, leading to similar asymmetries
- E665 smaller than HERMES because of smaller $\langle x \rangle$ (s quark contribution enhanced, leading to larger cancellations)

P_T: p_T dependence; averaged over z_h

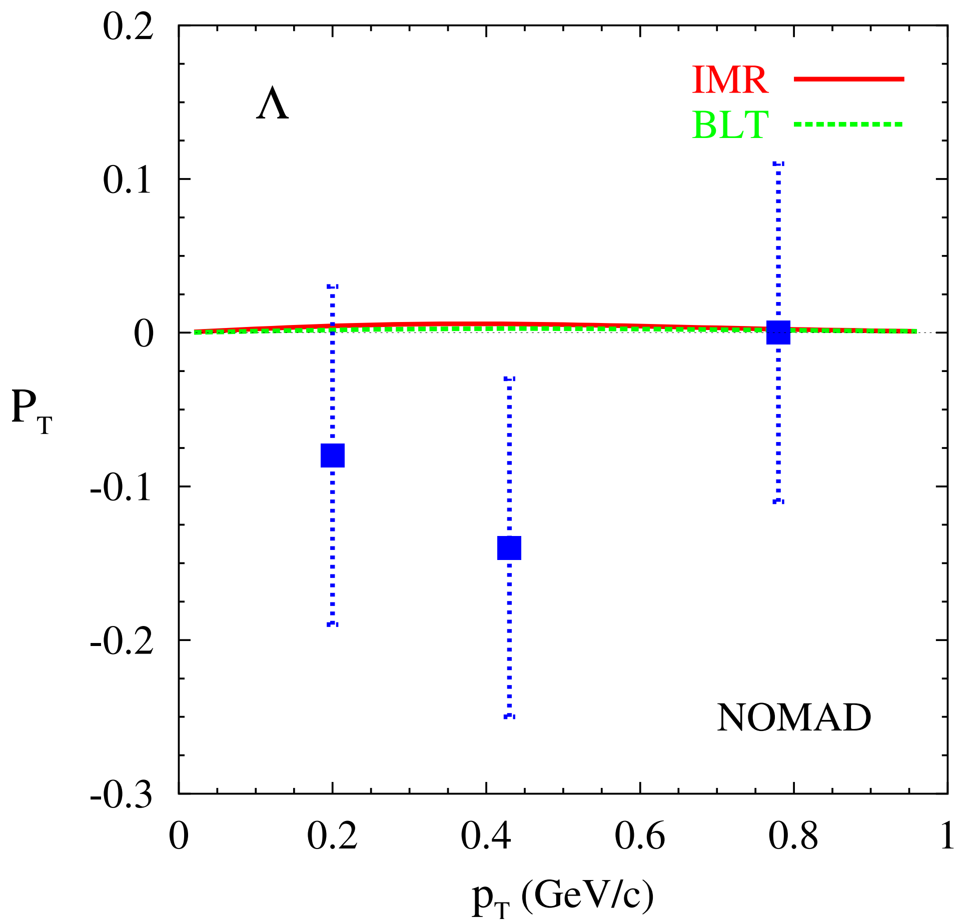




- Averaged over $0.4 < z_h < 0.8$
- Shape determined by the Gaussian model
- Including smaller z_h data leads to smaller asymmetries, due to the rising cross sections

Comparison to NOMAD data

These SIDIS results appear to have an opposite sign compared to NOMAD data
However, choosing the appropriate kinematics yields:

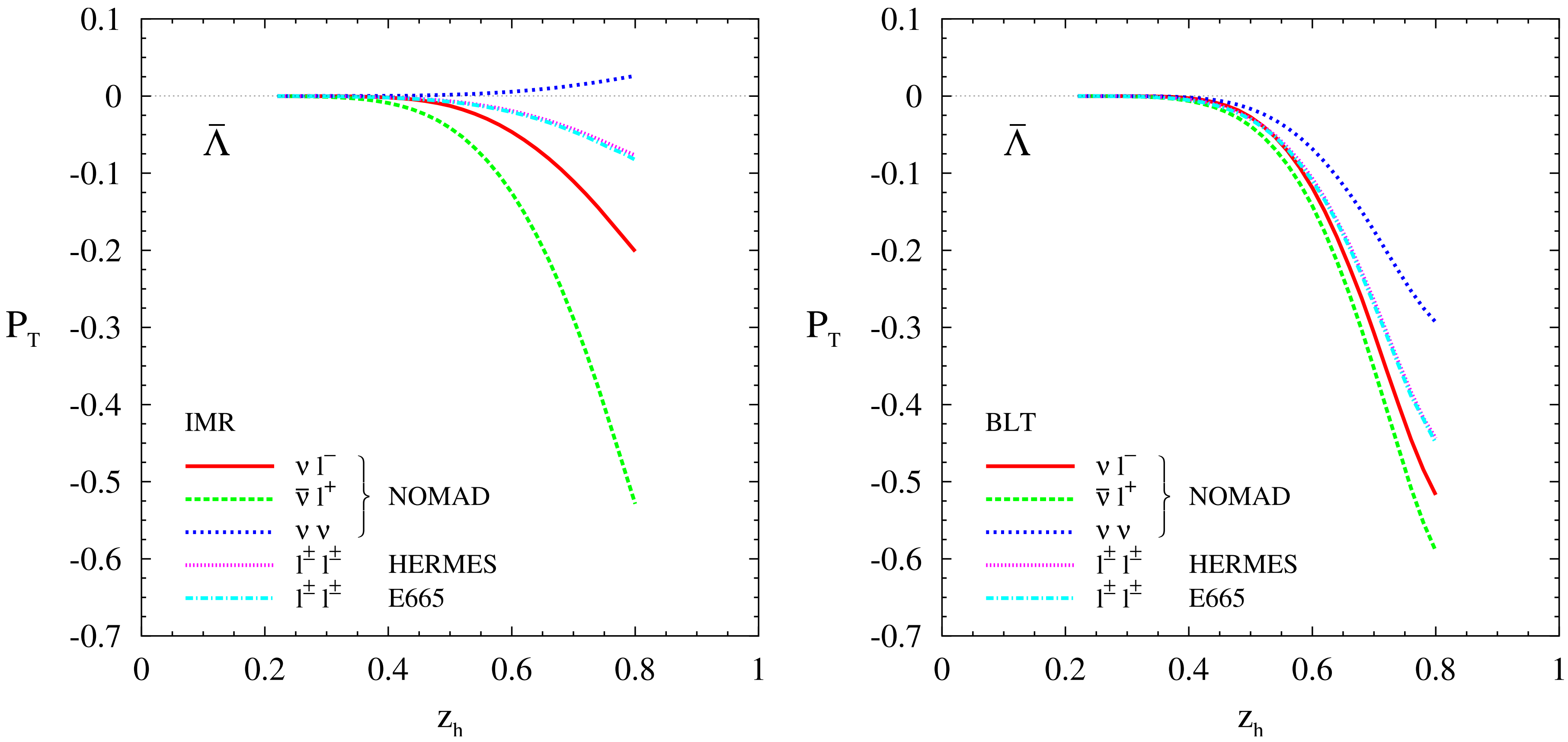


Data and curves are for:

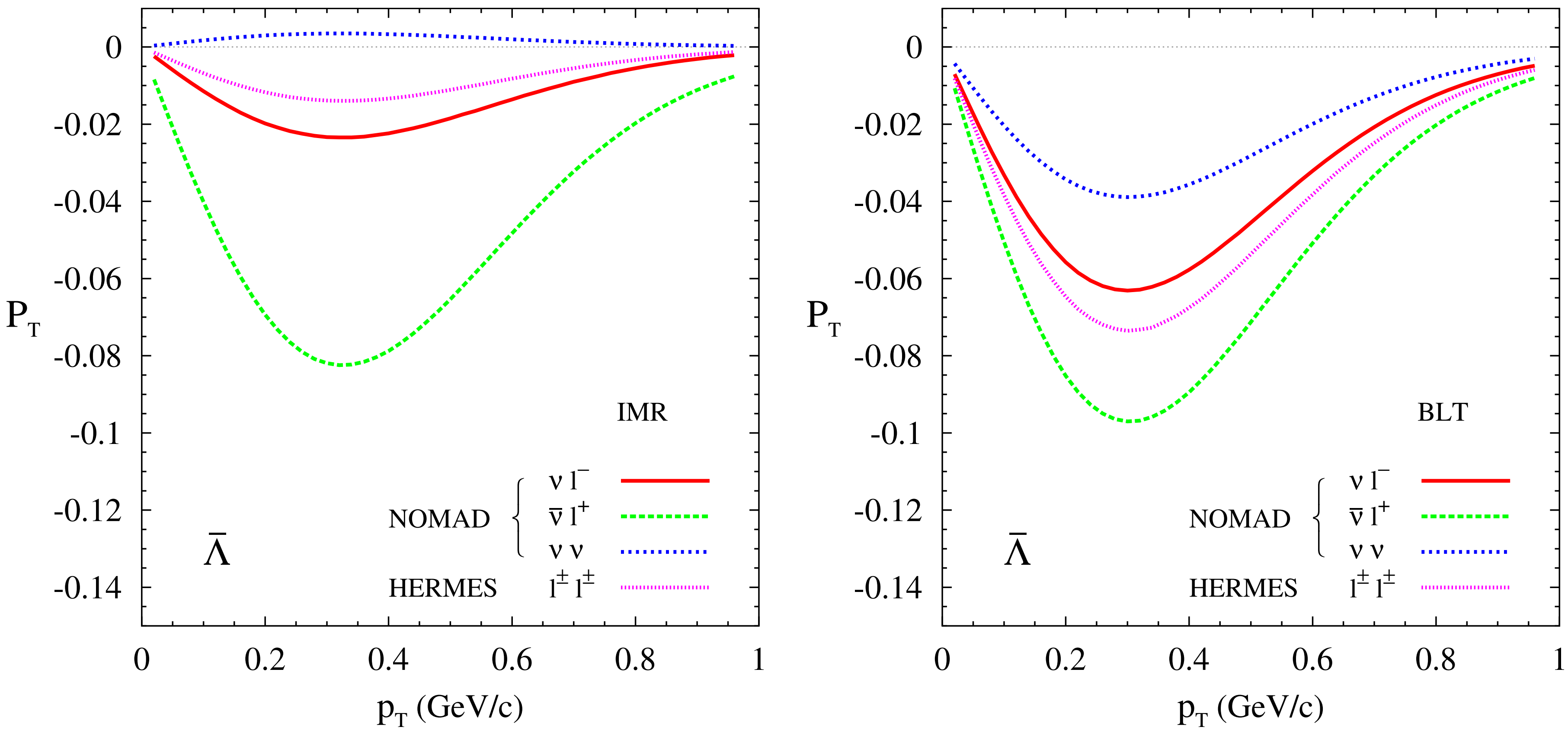
$< z_h >= 0.34$

$< x_F >= 0.21$

$\bar{\Lambda}$ polarization in SIDIS



$\bar{\Lambda}$ polarization in SIDIS



Jet-Λ production

High energy collider data

Validity of factorized description depends on proper cross section description
This requires data at higher energies and higher p_T

Why no data from high energy hadron colliders, such as RHIC or Tevatron?

Problem: capabilities to measure Λ polarization via $\Lambda \to p\,\pi^-$ are usually restricted to the midrapidity region, where the degree of transverse polarization is very small

$P_\Lambda = 0$ at $\eta = 0$ in $p\,p$ collisions in cms

If the origin of the transverse Λ polarization is indeed due to polarizing fragmentation, then another asymmetry could be observed that does not need to vanish at $\eta = 0$

D.B., Bomhof, Hwang, Mulders, PLB 659 (2008) 127

This is an asymmetry in the process $p\,p \to \left(\Lambda^{\uparrow}\text{jet}\right)\ \text{jet}\,X$

Jet-Λ production

Consider two jets, with momenta K_j and $K_{j'}$, such that $K_j \cdot K_{j'} = \mathcal{O}(\hat{s})$

The Λ is part of one of the two jets, and has momentum K_Λ and polarization S_Λ

An asymmetry can arise that is proportional to:

$$\epsilon_{\mu\nu\alpha\beta} K_j^\mu K_{j'}^\nu K_\Lambda^\alpha S_\Lambda^\beta$$

In principle, it is not power suppressed, nor needs to vanish at $\eta = 0$

In the center of mass frame of the two jets the asymmetry is of the form:

$$\text{SSA} = \frac{d\sigma(+\boldsymbol{S}_\Lambda) - d\sigma(-\boldsymbol{S}_\Lambda)}{d\sigma(+\boldsymbol{S}_\Lambda) + d\sigma(-\boldsymbol{S}_\Lambda)} = \frac{\hat{\boldsymbol{K}}_j \cdot (\boldsymbol{K}_\Lambda \times \boldsymbol{S}_\Lambda)}{z\, M_\Lambda} \frac{d\sigma_T}{d\sigma_U}$$

$d\sigma_T / d\sigma_U$ depends on $D_{1T}^\perp$

Jet-Λ production at the LHC

At LHC this process $p\,p \to (\Lambda^{\uparrow}\text{jet})$ jet X can be studied (at RHIC too of course)

For instance, ALICE can measure Λ's over a wide p_T range,

in a typical yearly run at least up to 16 GeV$/c$

Rapidity coverage of ALICE: $-0.9 \leq \eta \leq +0.9$

If jet rapidities are in this kinematic region, the cross section is dominated by gluon-gluon $(gg \to gg)$ scattering, *if* gluons fragmenting into Λ's are as important as quarks

This leads to

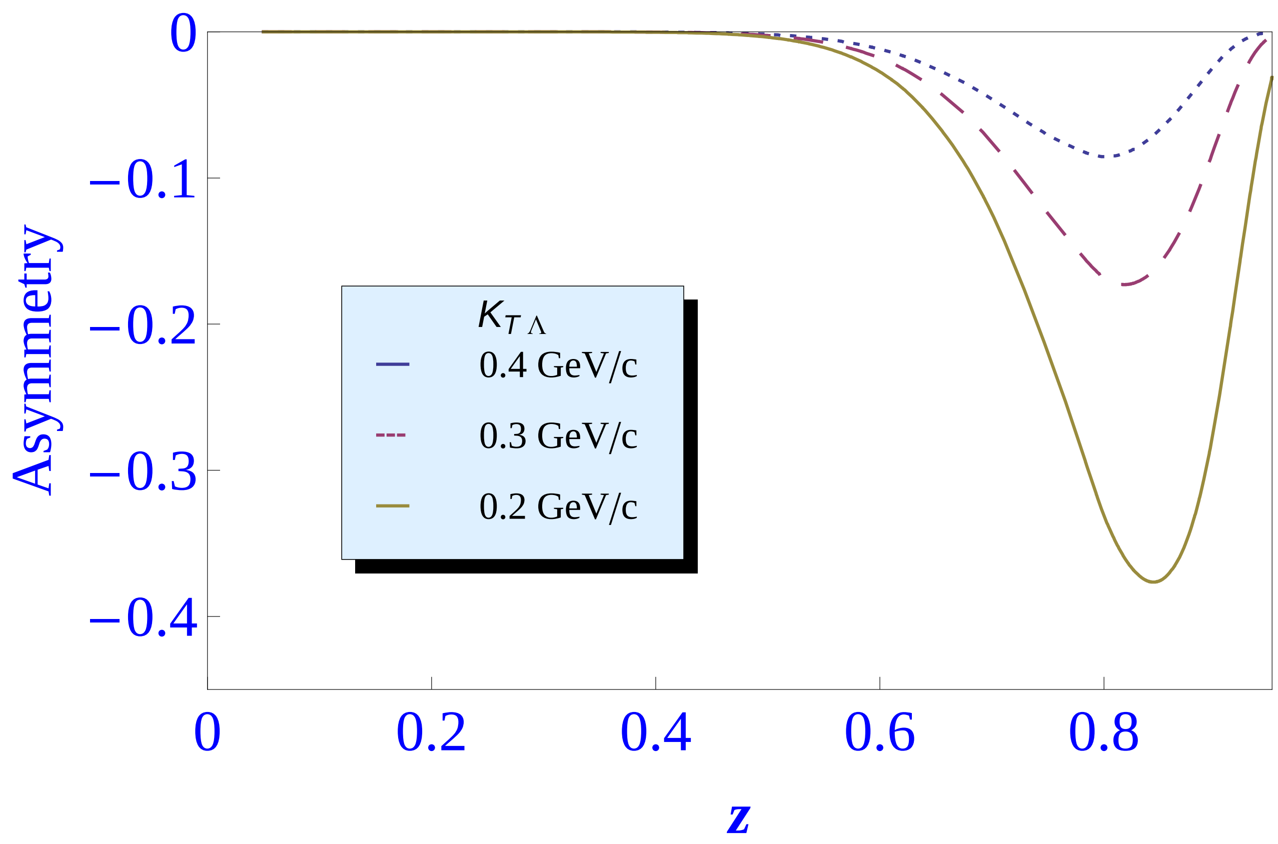
$$\frac{d\sigma_T}{d\sigma_U} \approx \frac{D_{1T}^{\perp\,g}(z, K_{\Lambda\,T}^2)}{D_1^g(z, K_{\Lambda\,T}^2)}$$

No model or fit for $D_{1T}^{\perp\,g}$ is available yet, so no predictions can be made in this case

Jet-Λ production at the LHC

If it happens that $D_{1T}^{g\,\perp} \ll D_{1T}^{q\,\perp}$, then one can use the extracted $D_{1T}^{\perp\,q}$ to get an estimate

For DSV (PRD 57 (1998) 5811) $D_1^g \ll D_1^q$ at larger z



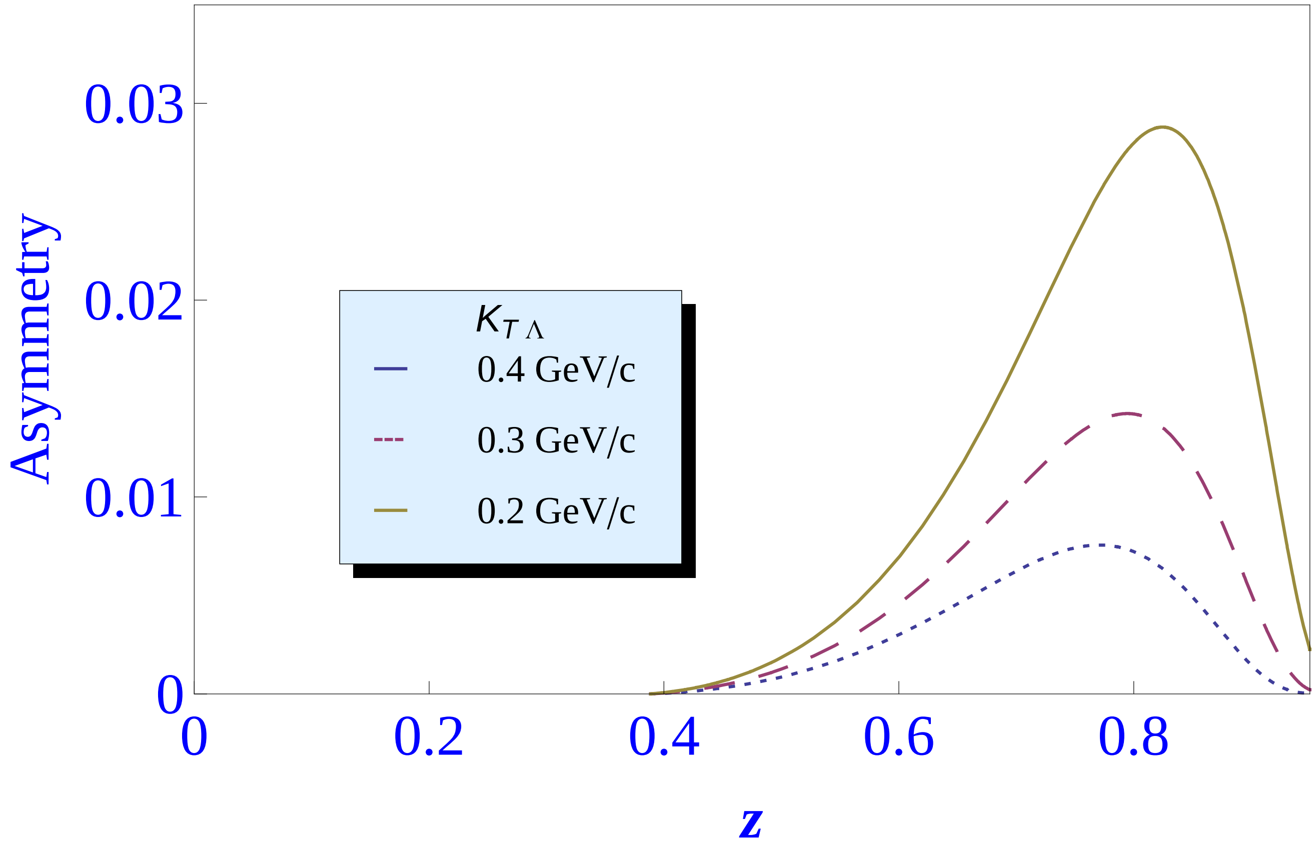
$\eta_j, \eta_{j'} = 0$

$|K_{\perp\,j}|, |K_{\perp\,j'}| = 70$ GeV

The asymmetry exceeds -1 for smaller $K_{T\Lambda}$ at large z, hence is overestimated

Jet-Λ production at the LHC

For Indumathi *et al.* [IMR] (PRD 58 (1998) 094014) one finds a very different result



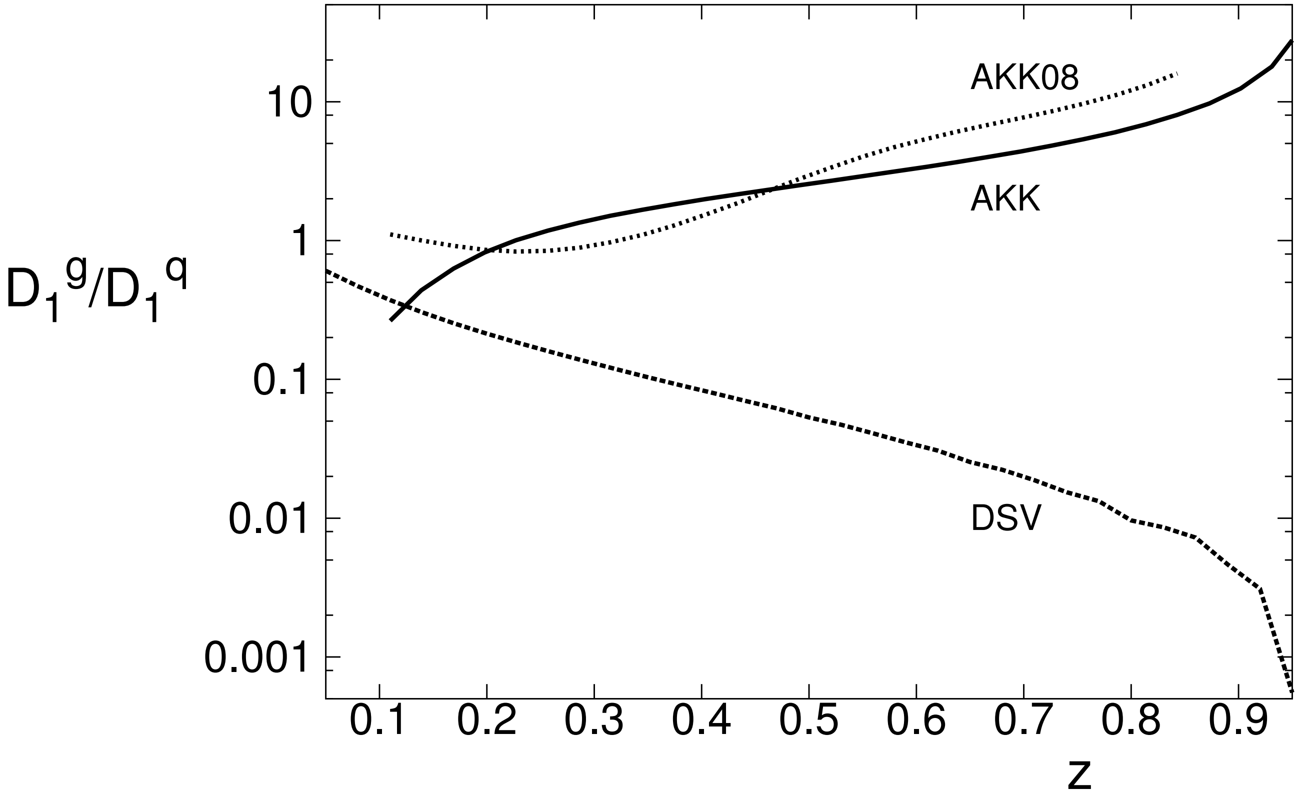
Asymmetry is very sensitive to the cancellation between u, d and s contributions

Role of $g \to \Lambda\, X$

Problems:

- fit of $D_{1T}^{\perp}$ to $p\,p \to \Lambda^{\uparrow}\, X$ data not sensitive to $g \to \Lambda\, X$
- fits of D_1 to only $e^+e^- \to \Lambda\, X$ data also not sensitive to $g \to \Lambda\, X$

AKK (Albino, Kniehl, Kramer, NPB 734 (2006) 50); AKK08 (NPB 803 (2008) 42)

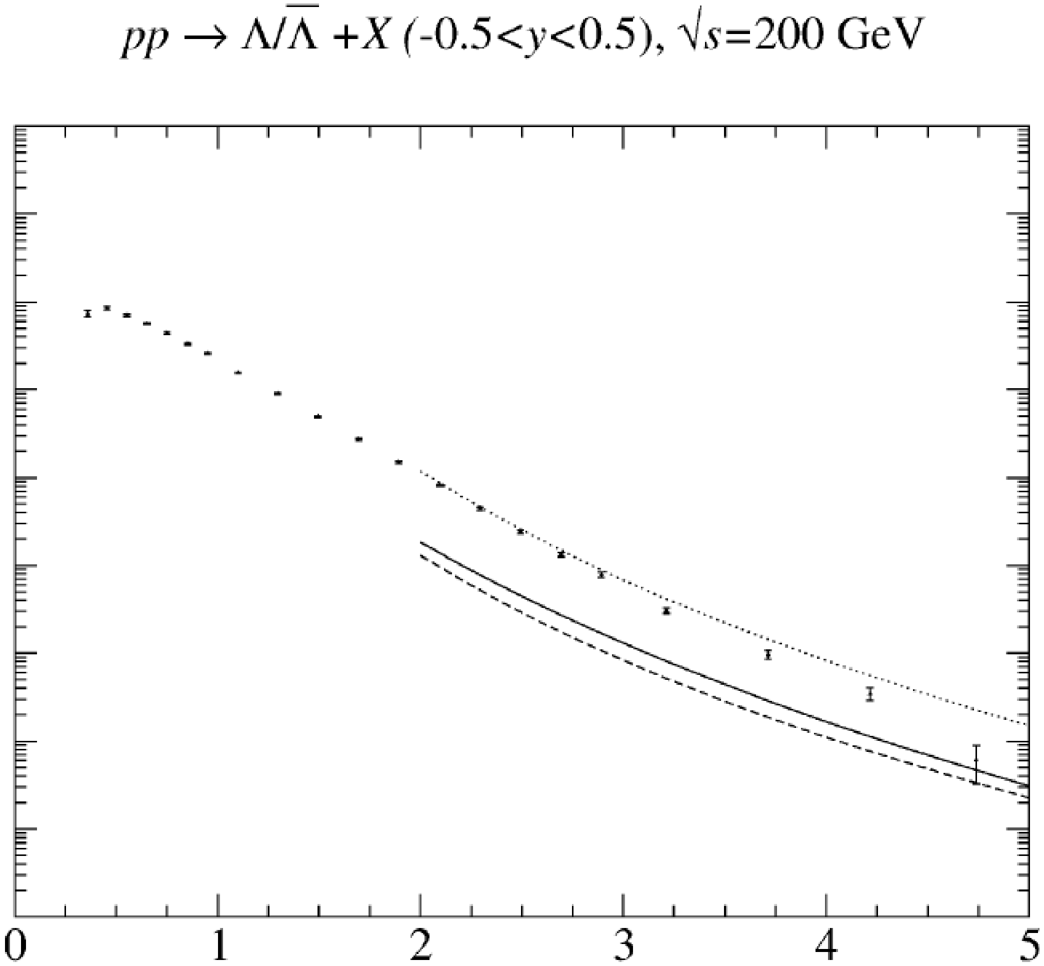


$Q = 10$ GeV

$q = u + \bar{u}$

Λ fragmentation function problem

AKK's 2008 update (NPB 803 (2008) 42) does not help



p_T distribution

solid: AKK08

dotted: AKK

dashed: DSV

data: STAR

"a possible inconsistency between the pp and e^+e^- reaction data for $\Lambda/\bar{\Lambda}$ production"

Conclusions on Jet-Λ production

Asymmetry in $p\,p \to (\Lambda^{\uparrow}\text{jet})\ \text{jet}\,X$ at midrapidity is very sensitive to $g \to \Lambda X$ aspects

Previous $D_{1T}^{\perp\,q}$ extractions of very limited use in predicting the asymmetry

Problem of unpolarized Λ fragmentation functions is serious
Cross section of $p\,p \to \Lambda\,X$ not well-described even at $\sqrt{s} = 200$ GeV

Forward $p\,A \to \Lambda^{\uparrow}\,X$

Forward rapidity data

Λ polarization is especially interesting in $p\,A$ reactions at very high $\sqrt{s}$, large A and η

In this kinematic regime of small x, saturation of the gluon density is expected

Would offer a direct probe of gluon saturation in both $p\,p$ and $p\,Pb$ collisions at LHC

The saturation scale Q_s and even its evolution with x could be probed in this way

D.B. & Dumitru, PLB 556 (2003) 33; D.B., Utermann, Wessels, PLB 671 (2009) 91

Forward rapidity data

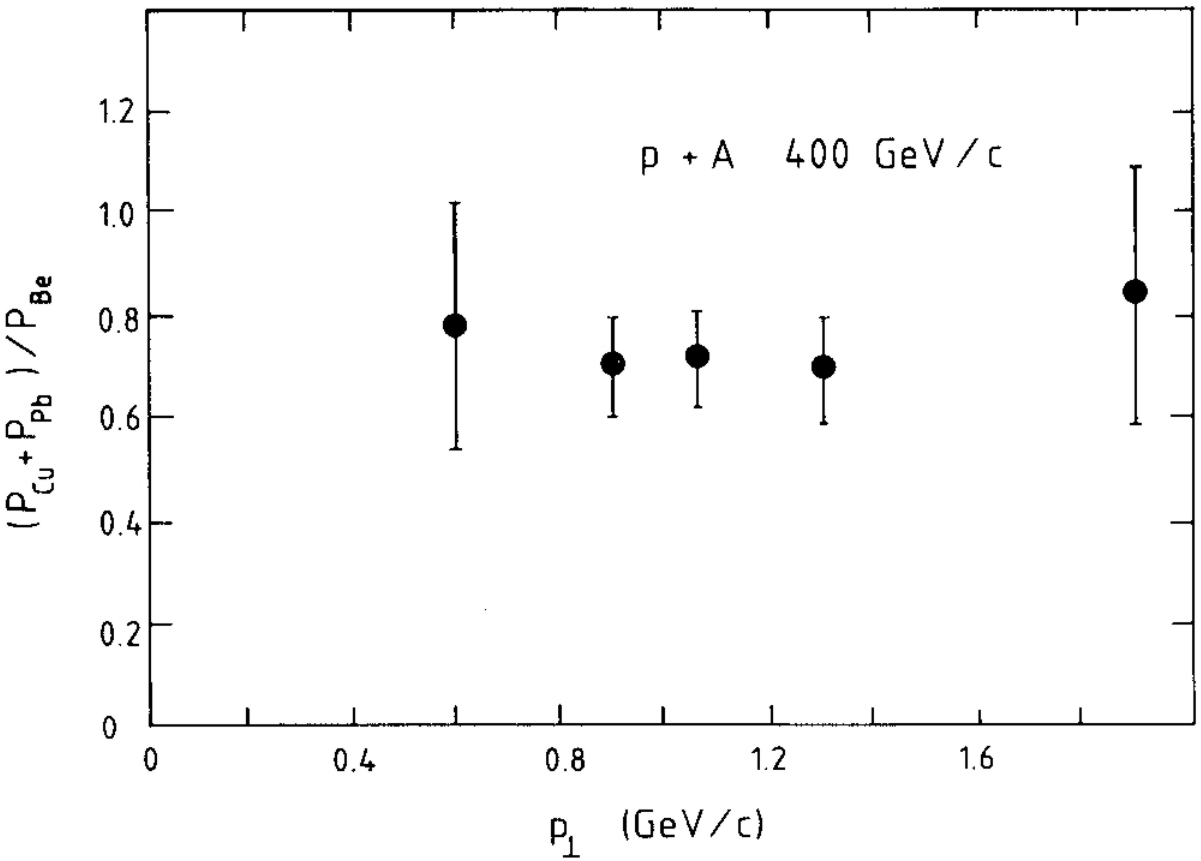
None of the existing data is in the saturation regime

In the forward direction often protons cannot be identified, which hampers the measurement of Λ polarization

Forward Λ's $(y = 2.75)$ in $d\,Au$ collisions have been identified via event topology
Abelev $et\ al.$, STAR Collaboration, PRC 76 (2007) 064904

Suggestion: use neutral decays $\Lambda \to n\,\pi^0$ to measure Λ polarization at forward rapidities

Heavy versus light nuclei in $p\,A$ [L. Pondrom, Phys. Rept. 122 ('85) 57]



Slight decrease of slope of asymmetry with increasing A as function of p_T is likely due to production of Λ's through secondary $\pi^- N$ interactions in nuclear matter

Hadron production in the saturation regime

The cross section of forward hadron production in the (near-)saturation regime:

pdf $\otimes$ dipole cross section $\otimes$ FF

Dumitru, Jalilian-Marian, PRL 89 (2002) 022301

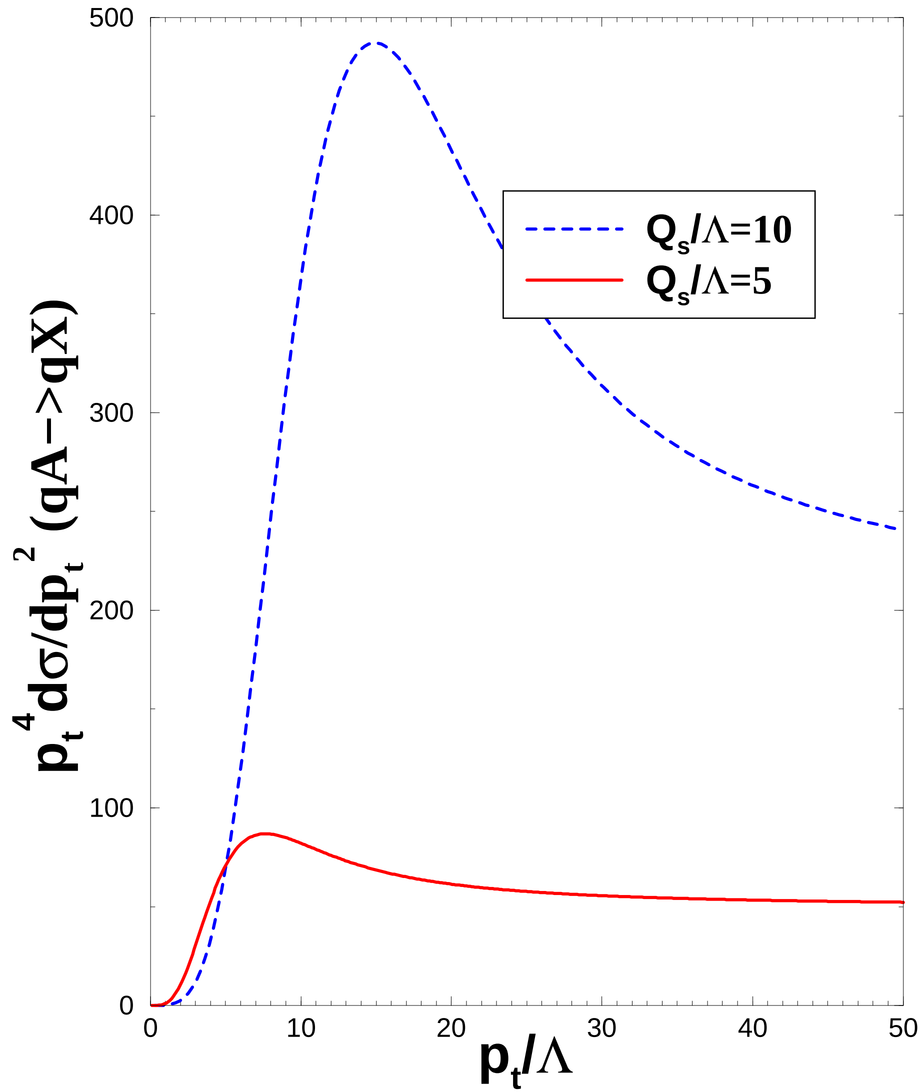
Since $D_{1T}^{\perp}$ is $\boldsymbol{k}_T$-odd, it essentially probes the derivative of the dipole cross section

At transverse momenta of $\mathcal{O}(Q_s)$ the dipole cross section changes much

This leads to a Q_s-dependent peak in the Λ polarization

First demonstrated for the McLerran-Venugopalan model, which has constant Q_s
McLerran, Venugopalan, PRD 49 (1994) 2233 & 3352

Saturation effects in $p + A \to \Lambda + X$

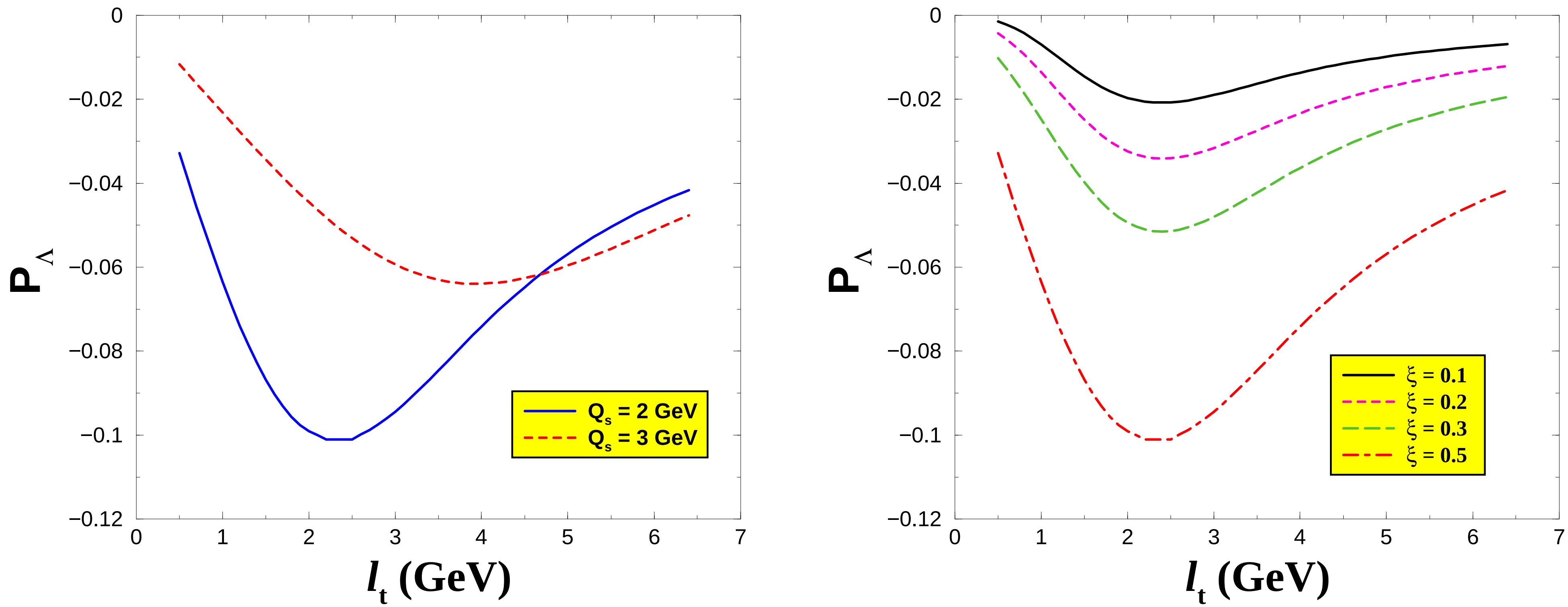


At high p_T, leading twist pQCD predicts:

$$\frac{d\sigma(q\,A \to q\,X)}{d\boldsymbol{p}_T^2} \sim \frac{1}{\boldsymbol{p}_T^4}$$

For $p_T \lesssim Q_s$ saturation effects modify the cross section

Λ polarization in $p + A \to \Lambda^{\uparrow} + X$



D.B. & Dumitru, PLB 556 (2003) 33

In the MV model, where Q_s is a constant, the peak is $x_F(= \xi)$ independent

Phenomenological models

The saturation scale actually changes with the small-x values probed:

$$Q_s^2(x) \propto \left(\frac{1}{x}\right)^{\lambda}$$

Models that incorporate this are for instance:

- GBW model, describes well small-x DIS data

  Golec-Biernat, Wüsthoff, PRD 59 (1999) 014017

- DHJ model, describes well forward $d\,Au \to \pi X$ RHIC data

  Dumitru, Hayashigaki, Jalilian-Marian, NPA 765 (2006) 464

- GS model, describes well $d\,Au \to \pi X$ and DIS small-x data

  D.B., Utermann, Wessels, PRD 77 (2008) 054014

Dipole scattering amplitude

The dipole scattering amplitude of phenomenological models:

$$N(q_t, x) \equiv \int d^2r_t \, e^{i\vec{q}_t \cdot \vec{r}_t} \exp\left[-\frac{1}{4}\left(r_t^2 Q_s^2(x)\right)^{\gamma(q_t,x)}\right]$$

GBW model: $\gamma_{\mathrm{GBW}} = 1$

It leads to geometric scaling: $N = N(q_T^2/Q_s^2(x))$

In DIS $(q_t = Q)$ geometric scaling of the cross section was observed for $x < 0.01$

Stasto, Golec-Biernat, Kwiecinski, PRL 86 (2001) 596

The saturation scale of the GBW model extracted from those DIS data:

$$Q_s(x) = 1\,\mathrm{GeV}\left(\frac{x_0}{x}\right)^{\lambda/2}$$

with $x_0 \simeq 3 \times 10^{-4}$ and $\lambda \simeq 0.3$

Geometric scaling at RHIC?

The DHJ model incorporates BFKL-type geometric scaling violations

$$\gamma_{\mathrm{DHJ}}(q_t, x) = \gamma_s + (1 - \gamma_s) \frac{\log w}{\lambda y + d\sqrt{y} + \log w}$$

where $w = q_t^2/Q_s^2(x)$, $\gamma_s = 0.6275$, $d = 1.2$ and $y = \log 1/x$

The geometric scaling model rises more quickly towards 1 as $q_t \to \infty$

$$\gamma_{\mathrm{GS}}(w) = \gamma_s + (1 - \gamma_s) \frac{(w^a - 1)}{b + (w^a - 1)}$$

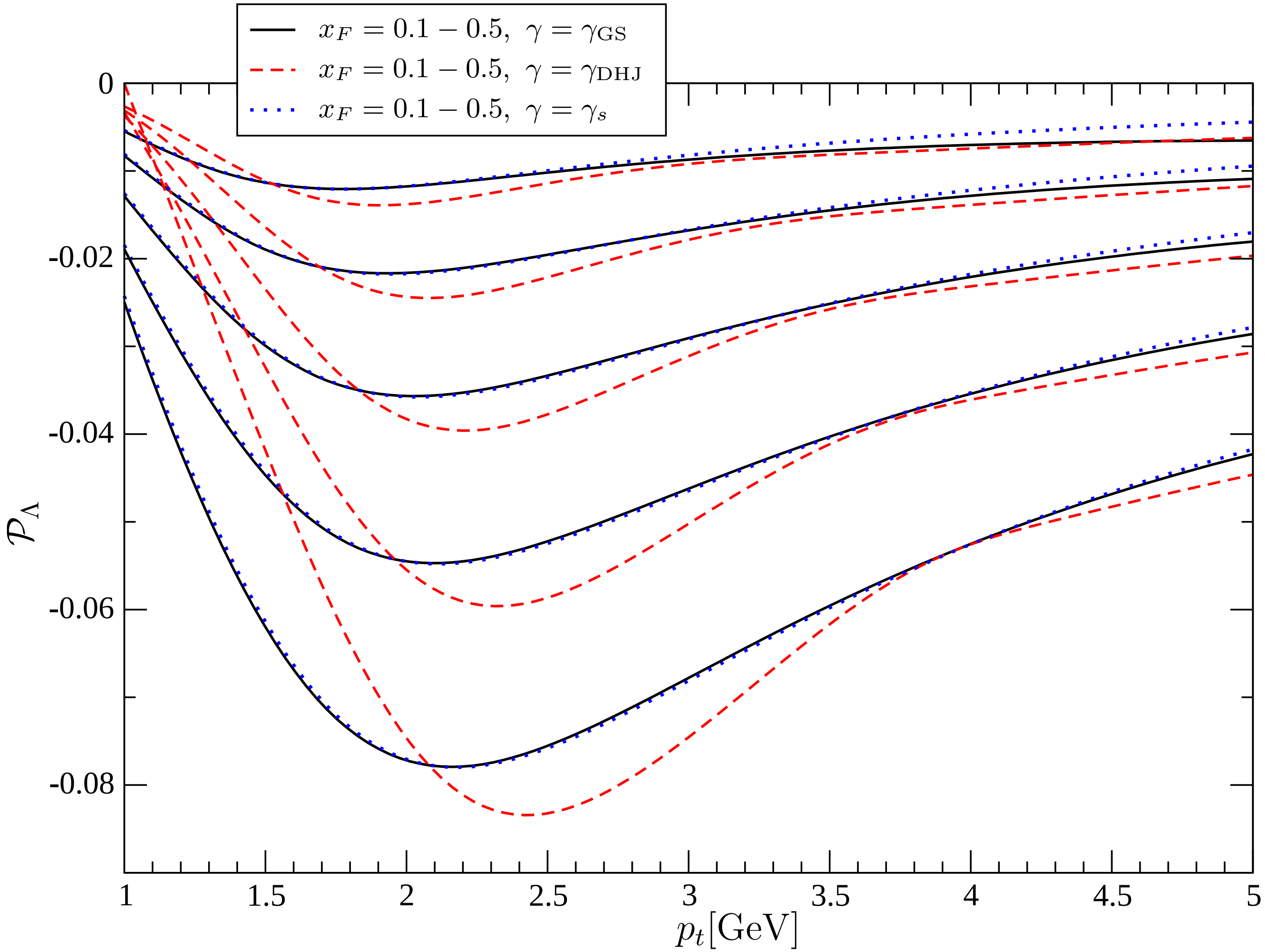
Here, $a = 2.82$ and $b = 168$ were fitted to the $d\,Au$ RHIC data

Both models describe well the forward pion production p_T spectra

DHJ and GS models lead to same conclusion about peak of Λ polarization:

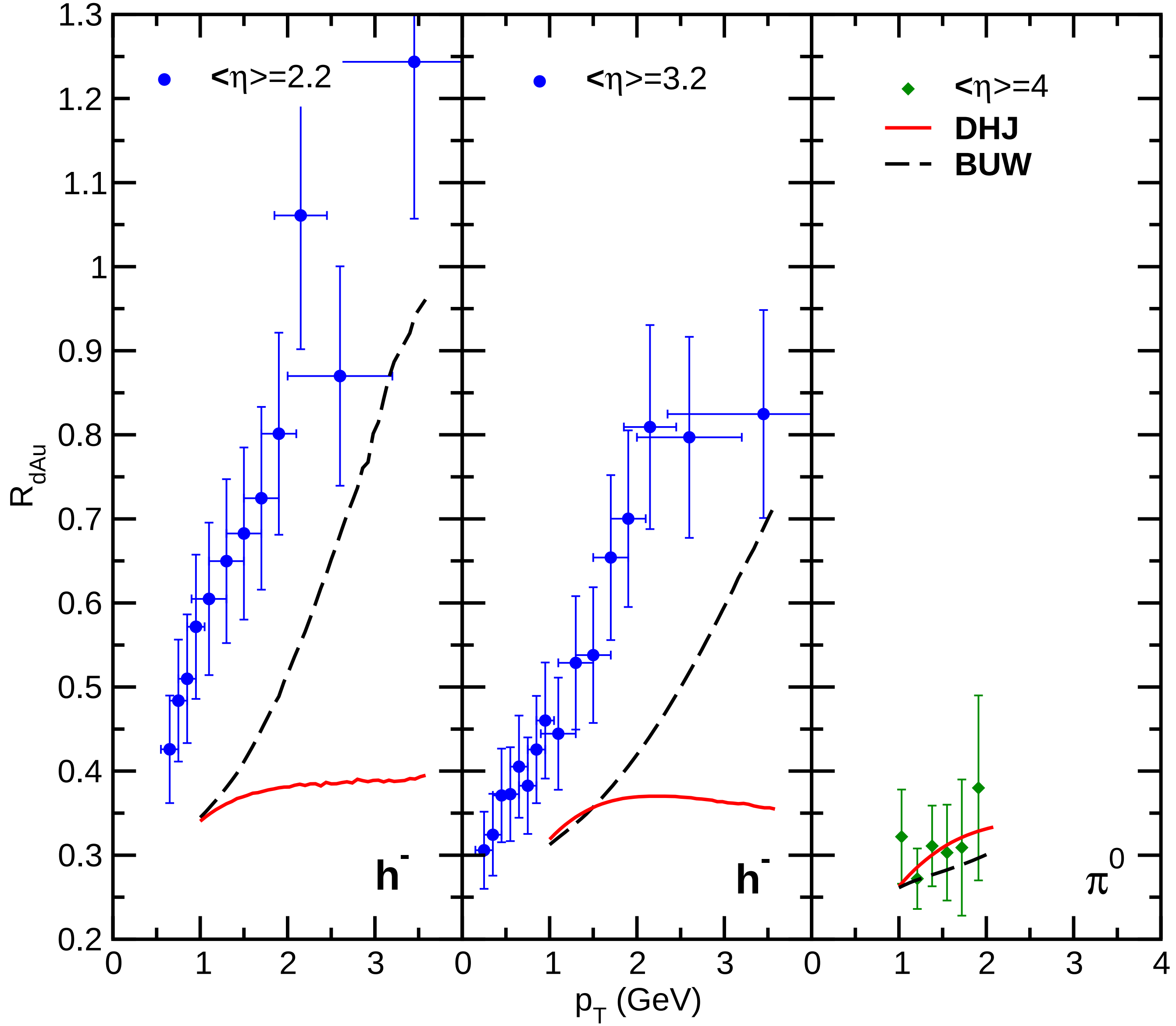
Its x_F dependence is to very good approximation the x dependence of Q_s!

Λ polarization in $p + Pb \to \Lambda^\uparrow + X$ at $\sqrt{s} = 8.8$ TeV



D.B., Utermann, Wessels, PLB 671 (2009) 91

R-ratio [Betemps, Goncalves, JHEP 0809 ('08) 019]



Conclusions on forward Λ polarization

Asymmetries in $p\,A \to \Lambda^{\uparrow}\,X$ can be used to study saturation physics

x_F dependence of the peak of Λ polarization directly probes the x dependence of Q_s

In principle possible at LHC (at RHIC the peak is likely at too low p_T)

Λ polarization studies at colliders could prove very interesting!